

Strange quark collectivity of ϕ meson at RHIC

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Abstract. Based on A Multi-Phase Transport model, the elliptic flow v_2 of ϕ mesons which is reconstructed from K^+K^- at the Relativistic Heavy Ion Collider (RHIC) energy has been studied. The results show that reconstructed v_2 of ϕ meson can keep the earlier information before ϕ decays and it seems to obey the number of constituent quark scaling as other mesons and baryons. This result indicates that the ϕ v_2 mostly reflects the parton level collectivity developed during the early stage of the collisions and the strange and light up/down quarks have similar collectivity properties before the hadronization.

Keywords: Elliptic flow, partonic interaction, AMPT model, ϕ -meson

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1. Introduction

Elliptic flow in heavy ion collisions is a measure of the azimuthal anisotropy of particle momentum distribution in the plane perpendicular to the beam direction [1]. It results from the initial spatial asymmetry in noncentral collision and the subsequent collective interaction is thus sensitive to the properties of the dense matter formed during the initial stage of heavy ion collision [2, 3, 4] and parton dynamics [5] at RHIC energies. The experimental results of charged kaons, protons and pions [6, 7] show that the elliptic flow first increases with particle transverse momentum following the hydrodynamic behavior and then tends to saturation in intermediate transverse momentum region. More importantly, a Number-of-Constituent-Quark (NCQ) scaling phenomenon of the elliptic flow has been discovered from this saturation region for baryons and mesons.

Strange quark dynamics is believed to be a useful probe of the QCD matter

created at RHIC. Enhanced strangeness production [8] has been proposed as an important signal for the QGP phase transition. The dominant production of $s\bar{s}$ pairs via gluon-gluon interaction may lead to strangeness (chemical and flavor) equilibration times comparable to the lifetime of the plasma and much shorter than that of a thermally equilibrated hadronic fireball. The subsequent hadronization is then expected to result in an enhanced production of strangeness particle. In particular, it has been argued that with the formation of QGP not only the production of ϕ -meson, which consists of $s\bar{s}$, is enhanced but they also retain the information on the condition of the hot plasma. It is believed that ϕ -meson interacts weakly in the hadronic matter and therefore freezes out quite early from the system [9]. Therefore the ϕ -meson in RHIC has been of great interest [10, 11].

We use a multi-phase transport (AMPT) model to investigate effect of parton dynamics on ϕ meson. AMPT model is a hybrid model which is consisted of four main components: the initial condition, partonic interactions, the conversion from partonic matter into hadronic matter and hadronic interactions. Details of the AMPT model can be found in [12]. In the default AMPT model [13] partons are recombined with their parent strings when they stop interaction, and the resulting strings are converted to hadrons using a Lund string fragmentation model [14]. In the AMPT model with string melting [15], a simple quark coalescence model is used to combine partons into hadrons.

In this work, we present a study for the elliptic flow of ϕ -meson at RHIC energy based on AMPT model with string melting scenario. We illustrate that the partonic effect could not be neglected for ϕ mesons as demonstrated for other hadrons in [15] and a string melting AMPT version is much more appropriate than the default AMPT version when the energy density is much higher than the critical density for the pQCD phase transition. So far, the AMPT model with string melting scenario has been successful to describe the elliptic flow of stable baryons and mesons [12, 15]. In this work, we try to investigate an unstable particle: ϕ meson. In order to compare with the experimental data, we adopt the value of particle mass with the mass width according to Breit-Wigner shape and then a broadening width of Breit-Wigner shape has been obtained when we reconstruct ϕ [16]. The value of the parton scattering cross section is chosen as 10 mb. The transverse momentum dependence and the collision centrality dependence have been studied and the NCQ-scaling phenomenon has been observed for ϕ -mesons. In addition, the rescattering effect of ϕ flow has been investigated in the hadronic scattering model, namely ART model which has been modified to include ϕ meson scattering processes [17].

2. Analysis Method

The azimuthal distribution with respect to the reaction plane at rapidity y can be written in a form of Fourier series as follows

$$E \frac{d^3 N}{d^3 p} = \frac{1}{2\pi} \frac{d^2 N}{p_T dp_T dy} \left(1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\Phi - \Psi)] \right), \quad (1)$$

where p_T is transverse momentum, Φ is azimuthal angle and Ψ is the reaction plane angle. The first and second Fourier coefficients v_1 and v_2 are called directed and elliptic flow, respectively.

Since ϕ -meson is unstable, it can only be reconstructed in final state from its decay products of either the K^+K^- pair or the lepton (e^+e^- or $\mu^+\mu^-$) pair. The present simulation results are reconstructed from the former decay products among $\sim 100,000$ events. All identified K^+ and K^- particles in a given event within the rapidity range of $(-1,1)$ are combined to form the invariant mass distribution. There are a large number of combinatorial background when the invariant mass distribution is reconstructed by K^+K^- pair. The combinatorial background are estimated by an event mixing method [18] in which all K^+ particles from one event are combined with K^- particles of ten other events within the same centrality. Then, the number of the combinational background are obtained after the normalized factor of the mixed event number (ten in our analysis). Finally, the yield in each bin is determined by fitting the background subtracted invariant mass distribution to a Breit-Wigner function plus a linear background in a limited mass range. Fig. 1 shows some examples in certain transverse momentum ranges for the reconstructed invariant mass spectra of ϕ mesons.

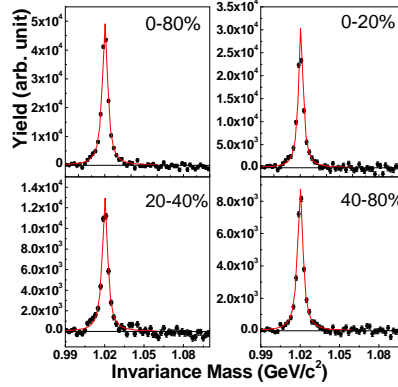


Fig. 1. The reconstructed invariant mass distribution (dots with statistical error bar) with the fits of Breit-Wigner function plus a linear background in the mass (GeV/c^2) range of $(0.98, 1.06)$ of ϕ -meson from K^+K^- pairs. From top-left to bottom-right it corresponds to the centrality of 0-80%, 0-20%, 20-40% and 40-80%, respectively. The azimuth angle range is $0-\pi$ and the p_T (GeV/c) range is 0.4 - 2.4 GeV/c . The FWHM from fitted function is 5.003, 5.073, 5.004 and 4.869 MeV respectively while the default value in AMPT model is 4.43 MeV.

The magnitude of the anisotropy and the finite number of particles available to determine the reaction plane leads to a finite resolution. Therefore, the reconstructed v_n^{rec} coefficients with respect to the reaction plane have to be corrected for

the reaction plane resolution [19]:

$$v_n = \frac{v_n^{res}}{\langle \cos(n(\Psi_n - \Psi_R)) \rangle}, \quad (2)$$

where Ψ_n is reconstructed event plane angle. The mean cosine values are less than unity thus this correction always increases the flow coefficients. After such correction, the flow should tend to the "true" flow which is supposed to be determined in true reaction plane.

3. Results

The upper panel of Fig.2 shows the elliptic flow v_2 of ϕ -meson from minimum-bias $^{197}\text{Au} + ^{197}\text{Au}$ collisions at $\sqrt{s_{NN}} = 200$ GeV. Experimental data [7] of $K^+ + K^-$ and $p + \bar{p}$ are also presented for comparison. First we observe that v_2 of ϕ -meson seems to follow the same behavior of $K^+ + K^-$: it is higher than baryon at low p_T region and then saturate in intermediate p_T region. The ϕ -meson v_2 is in agreement with the hydrodynamic model calculation [20] which predicts its mass ordering at low p_T region - perhaps implying that an early thermalized system has been created in collisions at RHIC energy. Compared with experimental data of $K^+ + K^-$ and $p + \bar{p}$, the reconstructed result can give a good description of the ϕ -meson v_2 within error bars.

One of the salient observations made at RHIC is a NCQ-scaling of the hadronic elliptic flow at intermediate p_T ($1.2 < p_T < 4.0$ GeV/c) [6] and the quark coalescence or recombination mechanism has been used to explain the NCQ-scaling [21, 22] in that p_T region. In this coalescence or recombination mechanism, hadron is formed via quark coalescence. The lower panel of Fig. 2 displays angular anisotropy of the constituent quark based on the quark coalescence picture. The behavior is similar for all reference particles for $p_T/n_q > 0.6$ GeV/c. The $v_2(p_T/n_q)$ represents a constituent quark momentum-space anisotropy v_2^q that may indicate a consequence of collectivity in a partonic stage which includes strange quarks. The reconstructed results give an implication that a new stage of partonic matter may be created with v_2^q characterizing the property of the matter.

As the $K^+ + K^-$ pair decaying from a ϕ -meson is likely to undergo appreciable re-scattering in the medium and this might lead to a reconstructed invariant mass situated outside the original ϕ -meson peak. In this case, the in-medium effect is necessary to be studied in details. It is carried out through turning off or turning on ART process [23] in AMPT model. It was found that the in-medium hadronic re-scattering effect on the final ϕ elliptic flow can be ignored within the errors. The reason is that the spatial anisotropy during the hadronic phase is small as well as ϕ has smaller hadronic interaction cross section. This may, however, depend on the hadronization scheme [15]. Our reconstructed result for ϕ v_2 confirms that it can keep useful information of ϕ -meson which is produced during the earlier collision.

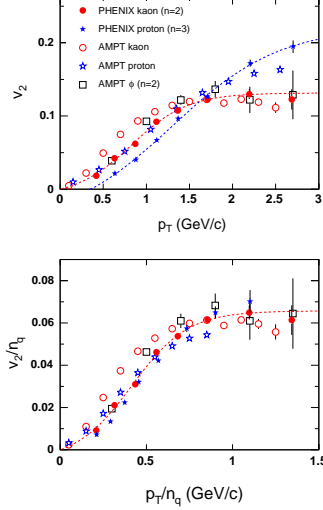


Fig. 2. Top panel: p_T dependence of the v_2 for ϕ -meson compared with $K^+ + K^-$ and $p + \bar{p}$. Data are taken from Ref. [7]. Dot-dashed lines are the fits results of function ($f_{v_2}(n) = \frac{an}{1+exp(-(p_T/n-b)/c)} - dn$, where a, b, c and d are the fit parameters, n is the constituent-quark number). Bottom panel: NCQ scaled v_2 . The error bars represent statistical errors only.

4. Summary

In summary, we have firstly presented the elliptic flow v_2 of ϕ meson from minimum-bias $^{197}\text{Au} + ^{197}\text{Au}$ collisions at $\sqrt{s_{NN}} = 200$ GeV in a multi-phase transport model with string melting scenario. The v_2 of ϕ -meson seems to demonstrate the similar behavior to other mesons. A NCQ-scaling phenomenon of elliptic flow reveals for ϕ from the reconstruction of K^+K^- pairs. The coefficient $v_2(p_T/n_q)$ of ϕ represents a constituent strange quark momentum-space anisotropy v_2^q that may arise as a consequence of collectivity in a partonic degree of freedom. It may imply that a new state of partonic matter has been created with v_2^q characterizing the property of the matter. The RHIC data for the elliptic flow of ϕ will shed light on these physics issues.

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Notes

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